THE VELOCITY AND RATIO $\frac{e}{m}$ FOR THE PRIMARY AND SECONDARY β RAYS OF RADIUM.

BY

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DISSERTATION

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BIOGRAPHY.

Samuel James MacIntosh Allen was born at Maitland, Nova Scotia on October 5th, 1877. His earlier education was gained in the public and private schools, and in the Halifax High School from which he graduated in 189[illegible]. In 1896 he entered the department of Electrical Engineering at McGill University, Montreal, Canada, and graduated with the degree of B.Sc. in 1900. On graduation he was appointed demonstrator in the Engineering Laboratories, where he was also engaged in research work on "The Flow of Water through Pipes and Bends", for which in 1901 he was awarded the degree of M.Sc. He was then appointed demonstrator in the Physical Laboratory at the same university, where he remained for the next two years engaged during a great part of the time in researches on "The Radioactivity of the Atmosphere", both in connection with Professor Rutherford and alone. The result of these investigations has been published in various articles in the Phil. Mag., Phys. Review, Phys. Zeit., and other journals.

In 1903 he entered the graduate department of Physics in the Johns Hopkins University, obtaining the Fellowship in Physics for the year 1903-04. During his course at this University he has studied under Professor Ames, Professor Wood, Professor Jones and Professor Morley- his

principal subject being Physics, first subordinate Physical Chemistry and second subordinate Mathematics.

Mr. Allen is a member of the Canadian Society of Civil Engineers and the American Physical Society.

INTRODUCTION.

The reasons which led the author to investigate this subject ought first to be briefly stated. While trying to demonstrate experimentally the magnetic and electrostatic deviation of the β rays from radium, by means of the electrical method, I was surprised to find that no appreciable electrostatic deflection could be obtained by the methods at first used, and that moreover the magnetic deflection observed was much less than we would be led to expect from the results of other experimenters. Considering the great importance of this subject, affording as it does the only method we have for testing the behaviour of the electron at speeds approaching that of light, it was deemed advisable to make a thorough investigation, and to find out, if possible, wherein lay the difficulties, and the non-success of the early experiments.

Before describing my own experiments it will be of interest to give a brief resume of the work done by previous investigators on this subject, and the conclusions reached by them. Becquerel[1] was the first to state

1. C.R. 130, 1900.

that the β rays from radium were deflected in an electrostatic field; and by measuring this deflection, and knowing from earlier experiments the deflection of the same rays in a magnetic field, he was able to calculate their velocity, and the ratio $\frac{e}{m}$. e being the charge in electro~~static~~ magnetic C.G.S. units, and m the mass expressed in grammes.

His experimental method might be briefly described as follows. A pencil of β rays was allowed to pass upward between two parallel brass plates, and to fall upon a photographic film, placed horizontally above them. The plates were insulated from one another, and maintained at a high difference of potential by means of an electrostatic machine. A thin sheet of mica was placed vertically in the path of the rays, so as to cut it into two halves. The image on the photographic film would thus be divided into two parts by a fine line in the centre. If now on the application of an electrostatic field the rays are bent, then there ought to appear on the image a shadow, the width of which would correspond to the least deviable ray.

Becquerel observed such a shadow, and measuring the width of it, and knowing from other experiments

the value of the magnetic deflection, he calculated the velocity of the β particle to be about 1.6×10^{10} cms. per sec., and the ratio $\frac{e}{m}$ as 1×10^{7}. This experiment of Becquerel was made in air at atmospheric pressure, and for this reason no very accurate estimate of the true electric field between the plates could be made, since the ionization caused by the β rays would to a great extent disturb the potential gradient. The results of Becquerel can therefore be only considered as approximate.

The method used by Kaufmann[1] to obtain the velocities of the β rays was entirely different and was based on the principle of crossed spectra. The heterogeneous pencil of rays from a small speck of radium passed upward between two brass plates, through a small hole in a metal diaphragm, placed horizontally above the plates, and then fell normally upon a photographic plate, wrapped in a thin exvelope of aluminium. The brassplates were insulated from one another and could be kept charged to a high difference of potential by means of a battery of small lead accumulators. The whole apparatus was enclosed inside a glass vessel from which the air could be exhausted. A magnetic field was

1. Nachr. d. Ges. d. Wiss. z. Gott., 1901.

applied parallel to the electrostatic and an exposure given for a certain time; the direction of the electrostatic field was then reversed, and a further exposure of the same time as before given, the direction of the magnetic field being the same in both cases. When the plate was developed there appeared on it two curved lines, showing that the β particles had been deflected by both the magnetic and electrostatic fields. By measuring the deflections observed, the value of the velocity, and $\frac{e}{m}$ for each ray could be calculated. He found that the velocities varied from 2.36×10^{10} to 2.85×10^{10}, and the value of $\frac{e}{m}$ from 1.31×10^{7} to $.63 \times 10^{7}$. Assuming that the charge is constant, these results showed that the mass of the electron apparently increased as the velocity of light was approached.

A theory has been developed by Thomson, and elaborated by Heaviside, Abraham, and others, whereby the mass of the electron is considered as entirely electrical in its nature, and increases with the speed of the electron, reaching at the velocity of light an infinite value. The late values of $\frac{e}{m}$ obtained by Kaufmann agreed very well with those as calculated from the formulae of Abraham. I shall discuss

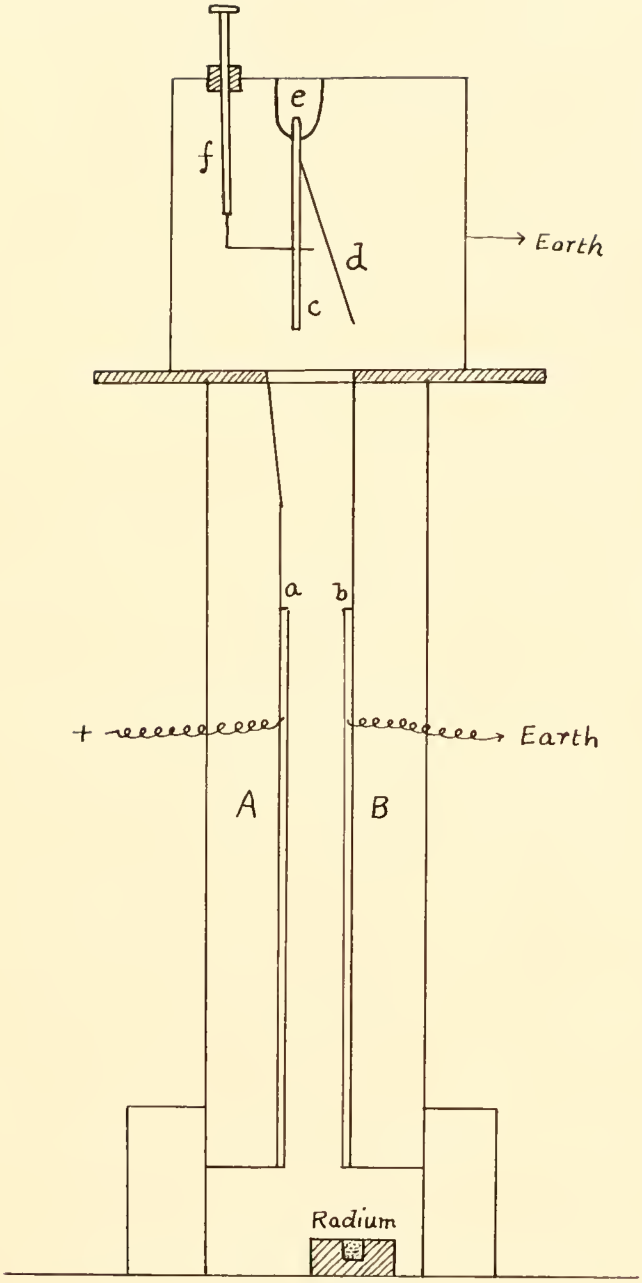
these results later on in this paper.

ELECTRICAL EXPERIMENTS.

The electrical method, whenever practical, is in some respects to be preferred to the photographic, in as much as many readings can be made and confirmed in the same time that it takes to make a single exposure by the latter. In my first experiments a sensitive Dolezalek electrometer was used, but it was found almost impossible to shield this and the connecting wires from electrostatic influences sufficiently to obtain accurate readings. It was therefore replaced by a sensitive gold leaf electroscope, which could be shielded very easily from the effects of the high potentials used.

Experiment I.

The first experiment was tried in air at atmospheric pressure, and the general arrangement is shown sketched in Fig. I. Two zinc plates 18 cms. long were attached to insulating uprights A and B, which kept them in a vertical position about 9 mms. apart. At the bottom of the plates was placed a block of lead containing some radium bromide, covered with a thin sheet of mica, which allowed the β rays to pass through



- Fig I -

without much absorption. The radium was so arranged that its extreme edge was in a vertical line with the plate b, thus causing the rays to graze the plate b, but allowing them to fall full upon the plate a.

Over the top of the plates was suspended the electroscope, the details of which are shown in the figure. The rod c containing the gold leaf was insulated from the case by means of a bead of sulphur e. The system was charged to a potential of a few hundred volts by means of the rod f, which could be turned so as to touch the rod holding the gold leaf. At other times it was connected to the case, which was earthed. The bottom of the electroscope had a thin aluminium window through which the rays could pass. The time which the gold leaf took to fall through a fixed distance on the cross hair of the telescope was taken as a measure of the ionization. Part of this ionization was due to the β and secondary rays, and part to the γ radiations, and these could be distinguished from one another by absorption tests. Of the total about 60% was due to the γ and the remainder to β and secondary rays.

If now the plate a is charged positively, then the β rays should be deflected away from the plate

b, and a decrease of the ionization observed. This decrease would be a measure of the deflection of the rays since no fresh rays could be bent in to take the place of those bent away. If the rays travel at different velocities, then this deflection would be only an average value, but by absorbing the ones of lower velocity one ought to be able to obtain the deflection of the high velocity rays very approximately.

The plates were maintained at a difference of potential by connecting them to a battery of small lead accumulators, from which a maximum potential of 5000 volts could be obtained. In the later experiments the number of cells was increased, so that a potential difference of about 9000 volts was available.

When a difference of potential of 5000 was applied to the plates no appreciable decrease of the ionization in the electroscope could be observed. The rays were completely deflected by means of a magnetic field, but the value of HR, H being the strength of the magnetic field, and r the raidus of curvature of the deflected rays, as calculated from this deflection was over five times what it should have been calculated from theory.

The expression for the deflection of the ray in a uniform electrostatic field is;-

$$\delta = \frac{X e d\left(\frac{d}{2}+h\right)}{m V^2}$$

where δ represents the deflection, d the distance travelled by the ray in the field, h the distance from the top of the plates to the electroscope, $\frac{e}{m}$ the ratio of charge to mass of the electron, X the strength of the electric field, and V the velocity of the electron. In this experiment d = 18 cms., h = 7 cms. and K = 5 x 10^{11} e.m. units.

If we assume for V, and $\frac{e}{m}$, the extreme values found by Kaufmann, viz., 2.83 x 10^{10} cms. per sec., and .63 x 10^{7}, the calculated value of the electrostatic deflection for the highest velocity rays amounts to about 11 mm. which should have been observed since the width of the window of the electroscope was only 15 mms.

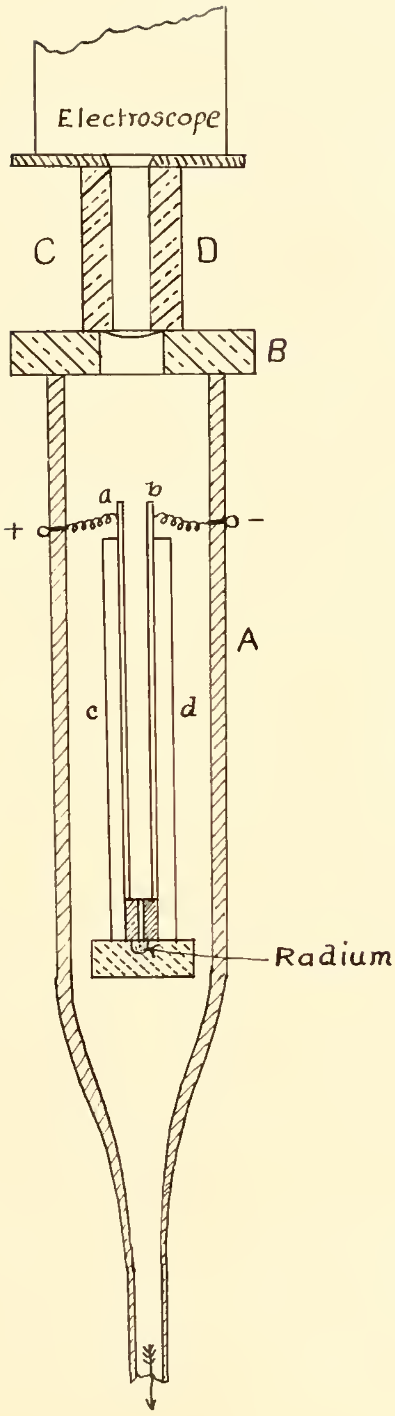
This failure to observe the electrostatic deflection could not at first be satisfactorily explained, and it was only after a number of experiments by different methods were made that the true explanation was reached. I shall discuss this point later on.

In this experiment, as in all others made in air at atmospheric pressure, we have no very definite knowledge of the uniformity of the electric field between the plates, and for this reason all the remaining experiments were carried out in a vacuum. In this case the plates can be placed closer together, and a much higher potential applied between the m without a discharge taking place, the field between the plates being practically uniform.

<u>Experiment II.</u>

In fig. II is sketched the general arrangement of this experiment. Two zinc plates, a and b, 6 cms. long are insulated from one another, and kept a distance apart of 2.9 mms. by means of ebonite side pieces. Beneath the plates are fastened two ebonite blocks, forming between them a slit of about 1 mm width, through which pass the rays from the radium contained in a capsule placed below. The capsule is covered with a thin sheet of mica, and sealed so that no emanation from the radium can escape into the surrounding vessel.

This apparatus was then enclosed inside a glass vessel A from which the air could be exhausted to a high vacuum. The top of the vessel was closed by means



- Fig II -

of a brass cap B, which had an opening cut through it, and covered with a very thin sheet of zinc. Two wires sealed through the glass were connected to the two plates, and served to charge them to any desired potential difference.

On top of the brass cap were placed two parallel brass blocks, 3 cms. long and at a distance apart of 1 cm., which supported the electroscope.

The rays from the radium passed upward in a diverging beam, through the thin sheet of zinc, and into the electroscope. When the vessel was exhausted to a high vacuum the plates maintained a potential difference of 5000 volts without a discharge; in this case we can assume that the electric field between the plates is uniform. When this voltage, which corresponds to an electric field of about 17000 volts per cm., was applied there was a decrease of about 10-15 per cent in the ionization due to β rays. The rays which reach the electroscope will consist in a large part of those of medium and high velocities, since the low velocity rays are mostly absorbed in the zinc plate. If we calculate as before the deflection which might be looked for we find it to be about 3.2 mms. for the highest velocity rays, and since the distance between

the plates at the electroscope is only 10 ms, this would amount to over 80% complete deflection. Those rays of lower velocity would be completely deflected. When the apparatus was placed in a magnetic field the rays could be completely deflected, though the apparent value of HR obtained was over three times what it might be looked for.

There was a slight possibility that some of the emanation might have escaped into the vessel, in which case the true effect would be to some extent masked by the rays coming from the emanation. In order to prevent this possibility another arrangement was devised where the radium was kept entirely outside the vessel containing the charged plates.

Experiment III.

The experimental arrangement is shown in fig. IV. A series of zinc plates, a , a , a , etc., 18 in number were arranged parallel to one another, being insulated and kept apart from one another by means of ebonite side strips. This arrangement was enclosed inside a glass vessel A, which had the walls blown out in thin bulbs immediately above and below the system of parallel plates.

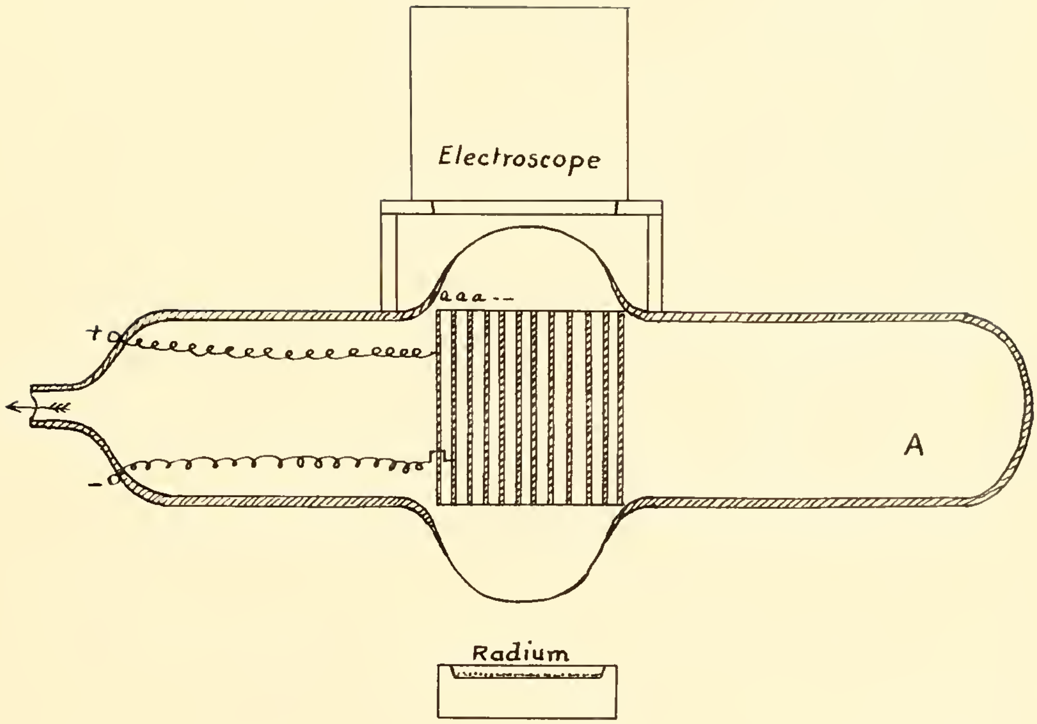


Fig IV

Alternate plates were connected together and to one electrode, the remaining plates being joined to the other electrode. The length of the plates was 4 cms., and the distance apart 1 mm. The radium was placed beneath the plates, and the electroscope above. By this arrangement a much greater amount of β rays could get into the electroscope than in the previous experiments, and also a large electric field could be produced between the plates. A small deflection of the rays should be readily detected in the electroscope. The radium was placed about 4 cms. from the bottom of the plates, so that the increase due to rays being bent so as to enter the electroscope could not be great enough to offset the decrease due to rays bent away and absorbed.

When a difference of potential of 5000 volts was applied to the plates no very appreciable deflection could be observed. The magnetic deflection was also considerably less than one might expect from theory. The total thickness of the glass walls would have about the same absorbing power as the sheet of zinc in the previous experiment.

The results of these experiments were at first very perplexing, and no very satisfactory explanation could

be reached. One was loath to conclude that the β rays were not deviable in an electrostatic field, since Kaufmann in his carefully carried out experiments obtained results which were in such extremely good agreement with theory. Besides, the disagreement of the magnetic results with those obtained by other experimenters, seemed to show that there was present some phenomena which were affecting both alike. Nothing has been said thus far in these experiments concerning the effect of the secondary rays which are produced when the β and γ rays strike upon various substances. This effect was from the first considered, and was thought to be too small to account for the results obtained, but, after some further experiments, the conclusion was reached that it played in all the experiments a large role and in some cases the principal one.

When the β rays, cut down to a narrow pencil by means of slits, were allowed to pass through an opening in the bottom of the electroscope considerably wider than the supposed width of the pencil, it was found, on placing a narrow strip of lead over the opening in different positions to cut off only a portion of the opening at one time, that the decrease in ionization

was the same for any part of the opening. This showed clearly that the rays coming through the opening were not confined to a narrow pencil as supposed but spread out into a diffuse, uniformly distributed beam.

A photographic plate placed over the opening showed on development a broad, uniformly dense image instead of the sharp narrow one, which ought to be made by the β rays alone. This broadening of the pencil of the rays is unquestionably caused by the secondary radiation produced by the primary β and γ rays. If this secondary radiation was of the nature of γ rays, then it would not be deflectable in a magnetic or electrostatic field, and could consequently not affect the observed deflection of the β rays, but if on the other hand it was of the nature of the primary β rays, and therefore deflectable, great confusion would arise from the different radiations.

The secondary radiation produced by β and rays of radium has been the subject of investigation by McClelland[1], Eve[2], and Kucera[3], who found that in general it is of several kinds, both deflectable and non-deflectable in a magnetic field, and of different penetrating power. No definite knowledge was obtained of the veloc-

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1. Phil. Mag. Feb 1905
2. Phil. Mag. Dec 1904
3. Annalen der Physik. 1906

ities of the deflectable kind, and to this purpose the author decided to make a complete investigation of the secondary rays. Before giving an account of this investigation I would like to describe two experiments on the β rays made by the photographic method.

PHOTOGRAPHIC EXPERIMENTS.

Experiment I. - The arrangement used in this is essentially the same as that used by Becquerel[1] and is shown sketched in fig. V. Two metal plates a and b 4.2 cms. in length were placed parallel to one another in a vertical position 6 mm apart, and insulated by means of ebonite. About 2 cms. below the plates was placed the radium, contained in a narrow crevasse in a block of lead. In the centre of the radium, and midway between the plates was fastened a sheet of mica c, which extended from the radium up to the photographic plate e. This plate was wrapped in a sheet of black paper, and then placed inside a light tight box containing a thin aluminium window through which the rays could pass without much absorption. The distance between the top of the metal plates and the photographic plate was 2.4 cms.

When the plates a and b are uncharged there ought to be obtained on the photographic plate an image crossed

1. loc. cit.

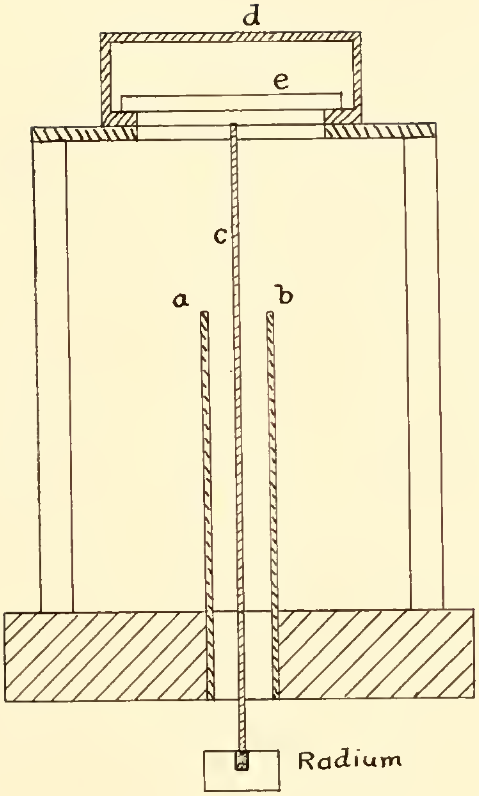

Fig. V.

in the centre by a narrow band. On the other hand when the plates are charged to a high potential, if the rays are deflected to one side, the photographic plate should show a broad shadow cast by the mica screen. In A and B, fig. 6, are shown two photographs obtained by this method, A taken without an electric filed, and B with a potential difference between the plates of 3000 volts, corresponding to a field strength of 6000 volts per cm. Both photographs appear precisely alike and show no indication of any shadow on the plate. One side in both photographs appears darker than the other; this is on account of the mica screen not being placed exactly in the middle of the radium, thus throwing more rays to one side than to the other. In C & D are shown two photographs taken with the screen placed exactly in the centre, C being without a field and D with one; and both sides of the image now appear equally dense. These photographs were all taken with the radium covered with a thin sheet of mica, so that no emanation could escape and affect the plate. Experiments were also tried with the radium uncovered, and the same results were obtained as before. Radium when dry and at ordinary temperatures does not give off very much emanation.

Fig. VI.

<u>Experiment II.</u>- The arrangement used in this experiment, and illustrated in fig. 7, is essentially the same as that used by Kaufmann[1] in his work. Two brass plates, a and b, placed parallel to one another inside a brass box A, were insulated from the sides by means of ebonite bushings c and d. Beneath the plates was fastened a small speck of radium bromide, and above the plates a thick ebonite screen which had a hole 0.5 mm cut in it, through which the rays could pass in a narrow pencil. At the top of the brass box was placed a photographic plate wrapped in a sheet of black paper. The whole apparatus was enclosed inside a glass vessel which could be exhausted to a high vacuum.

Exposures of one, two and four days were made, with and without an electric field, but in no case could any sharp image due to β rays be obtained on the plate, the only effect being a darkening of the whole plate due to γ and secondary radiations. When the radium was left uncovered the darkening of the whole plate was much greater, due to the emanation diffused throughout the vessel.

In another arrangement a larger quantity of radium contained in a lead capsule was placed outside the brass box, and the rays allowed to enter through a small hole,

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1. loc. cit.

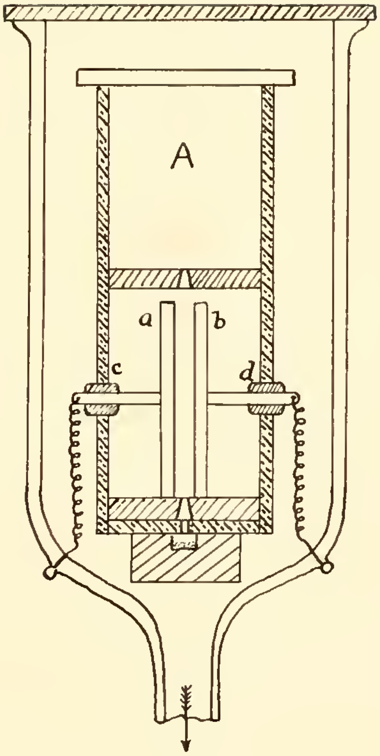


Fig. VII.

and thence through an ebonite diaphragm placed just beneath the brass plates a and b.

This failed to give any better results than before; and all further attempts to repeat Kaufmann's experiment were then abandoned. Probably with better photographic skill in restraining the darkening effect due to the rays I might have succeeded in obtaining a clear image of the β rays. The radium used in this experiment was some kindly loaned me by Professor Rutherford, and was as strong, if not stronger, than that used by Kaufmann in his last experiments.

SECONDARY RADIATION.

The experimental arrangement used to study the secondary radiation is shown diagramatically in fig 3. About 300 milligrammes of radium bromide of about 30000 activity was sealed in a very thin glass tube of 1.5 mm diameter and about 5 cms. long. This tube was enclosed inside a lead box a, which had a slit 5 cms. long and 1 mm wide cut in one side, the walls of the lead box being of such a thickness that no β rays could pass through. This box was cemented to two thick ebonite blocks b and c in such a manner, that one edge of the slit coincided

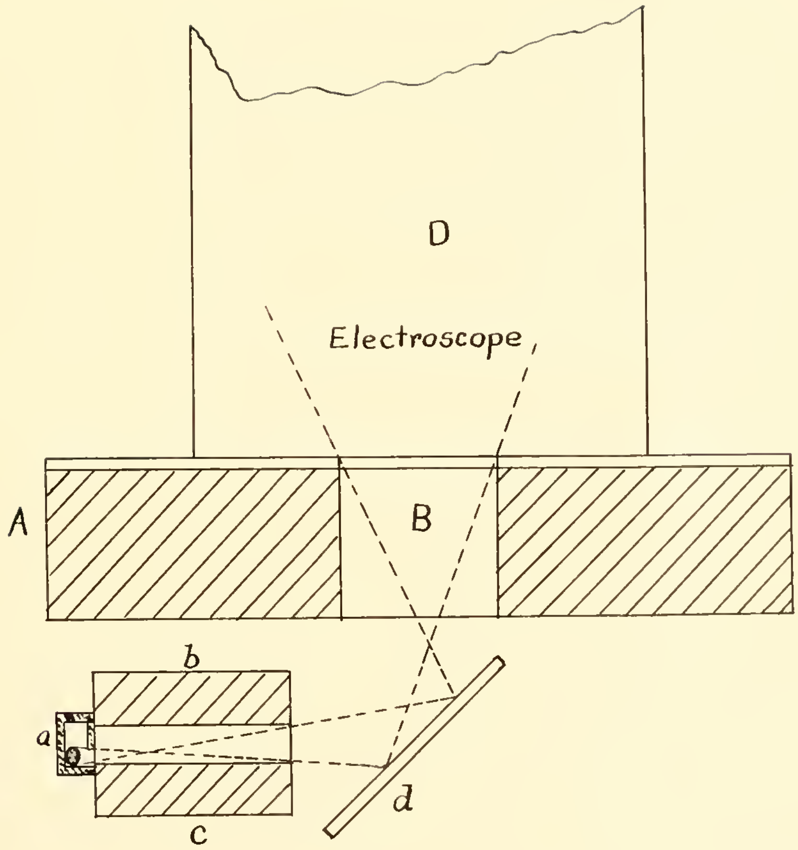


Fig. VIII.

with a face of one of the blocks as indicated in the figure. A divergent beam of β rays thus emerged from the slit, and was limited in width by the walls of the ebonite blocks. This apparatus was placed so that the rays travelled in a horizontal direction.

Directly above and parallel to the ebonite blocks was supported a thick screen A, constructed of cardboard and filled with mercury, and having in the centre a wide rectangular opening through which the radiations could pass into a gold leaf electroscope placed above. The substances which were to be studied as sources of secondary radiation were placed beneath this opening in such a position that the β rays fell full upon them. The thick mercury screen absorbed a large part of the radiation; and although it introduced a small amount of secondary radiation, this increase was more than offset by the decrease of the rays. The ionization in the electroscope due to the secondary radiation from below would under these conditions form a much larger proportion of the whole, than when the full rays were present.

When the radiator d is not present, the ionization in the electroscope is due to γ rays and the secondary rays produced by them.

When the radiator is placed in position this ionization

will be increased by that due to the secondary rays from below. By fixing radiators of different materials in the position d, and placing screens of varying absorbing power under the opening B, a knowledge of the relative penetrating power of the secondary radiations from the different radiators can be obtained. When a thick screen is placed so as to cut off the β rays, then the increase of ionization will be due to the secondary rays caused by the γ rays striking the radiator d.

In table I are shown a characteristic series of readings for different radiators, under various conditions

TABLE I.

Radiator - Air and Surrounding Objects.

Total Rate of Leak.	Rate of Leak due to Secondary Rays.	Absorbing Material.	%Unabsorbed Rays.	Remarks.
3.61	1.01	0	100	No radiator at d.
3.02	0.42	4 sheets paper	41	Paper placed on
2.94	0.34	8" "	34	top of Mercury
2.85	.25	16 "	25	cury screen.
2.70	.10	34 "	10	
3.28	.68	50 "		Paper placed below
3.29	.69	0		screen placed over β rays.

Radiator - Zinc.

Total rate of leak.	Rate of leak due to Secondary Rays.	Absorbing Material.	Unabsorbed Rays.	Remarks.
10.20	7.10	0 Paper	100	In this set
8.85	5.75	2 "	81	of readings
7.76	4.66	4 "	66	the absorbing
6.21	3.11	8 "	44	layers of paper
4.74	1.64	16 "	23	were placed
4.09	.99	24 "	14	directly over
3.53	.43	40 "	6	radiator d.
3.28	.18	60 "	2.5	

Radiator - Zinc.

5.00	1.90	0 "	100	β rays partly
4.51	1.41	4 "	74	screened by 24
4.18	1.08	8 "	57	sheets of
3.80	.70	16 "	37	paper

Radiator - Zinc.

3.82	0.72	0 "	100	β rays screened
3.59	.49	20 "	68	by piece of
3.42	.32	36 "	44	zinc.
3.31	.21	86 "	29	

	Total Rate of leak.	Corrected leak.	Absorbing Material.	Unabsorbed Rays.	Remarks.
	3.82	0.72	0	100	Zinc screen over β rays.
	3.30	.20	0	100	2 Zinc screens over β rays.
	3.24	.14	100	70	2 Zinc screens over β rays.
	Air. 3.10	.00	0	0	radiator removed.
Radiator	4 sheets of	Paper.			
	4.96	1.86	0	100	
	4.18	1.08	4	58	
	3.69	.59	8	31	
	3.34	.24	10	13	
	3.21	.11	32	6	
Radiator	8 sheets of	Paper			
	5.29	2.19	0	100	
Radiator	16 sheets of	paper			
	5.81	2.71	0	100	
Radiator	28 sheets of	Paper			
	6.45	3.35	0	100	
	4.80	1.70	4	51	
	4.13	1.03	8	31	
	3.57	.47	16	14	
	3.29	.19	32	6	
	3.23	.13	62	4	
Radiator	Glass				
	7.52	4.42	0	100	
	4.86	1.76	8	39	
Radiator	Lead				
	11.36	8.26	0	100	
	6.85	3.75	8	15	

Radiator Copper.

Total Rate of leak.	Corrected Leak.	Absorbing Material.	% Unabsorbed Rays.	
8.78	5.68	0	100	
Radiator Iron.				
8.69	5.59	0	100	
5.34	2.24	8	40	

From a study of these results we see at once that, substances when struck by β rays give out secondary rays, which differ amongst themselves both in quantity and penetrating power.

In order to produce the maximum amount of secondary rays the substance has to be of sufficient thickness to completely absorb all the β rays which fall upon it. The amount of secondary radiation due to the γ rays is only a very small quantity of the total, provided the thickness of the radiator is only just sufficient to absorb all the β rays. When only the most penetrating β rays are allowed to fall upon the radiator, the secondary radiations produced are on an average of a much more penetrating nature, than when all the β rays are present. This is partly due to the fact that the secondary rays due to the high velocity β rays are more penetrating, and also partly to the presence of a small amount of secondary γ rays caused by the primary rays.

The denser a substance is, the greater will be the amount of the secondary rays produced, and the greater their penetrating power. Of those substances examined, lead proved to be the most efficient, and also gave rays of the most penetrating power, while paper was the least. For the sake of comparison I give in table II the results of an absorption test on the primary β rays, (which of course contained a certain amount of secondary rays), together with the results obtained for the secondary radiation from zinc and paper.

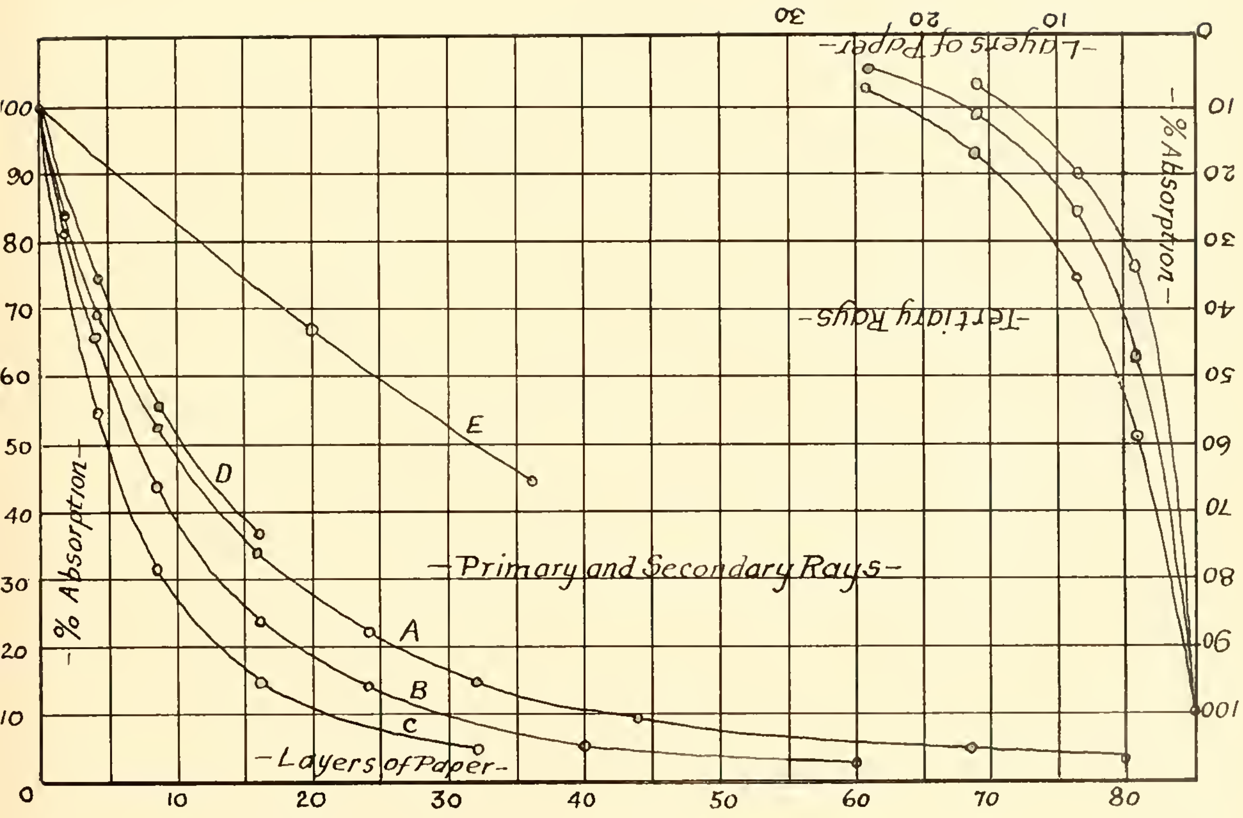
TABLE II.

Layers of Paper.	Primary β rays	Secondary from Zinc	Secondary from Paper.
0	100	100	100
2	82	81	
4	70	66	51
8	52	44	31
16	33	23	14
24	22	14	
32	15		6
44	9.7	5.8	
60	5.0	2.5	

The penetrating power of the secondary rays from zinc does not differ very greatly from that of the primary β rays, especially for the first few sheets of paper. The penetrating power of the secondary rays from lead is only slightly greater than that of the rays from zinc.

In fig. 9 are drawn several absorption curves, both for the primary β rays, and for the secondary rays. A represents that for the β primary rays, B that for the secondary rays from zinc, C that for the secondary from paper, D the secondary from zinc when the primary β rays have passed through 25 sheets of paper, and E that for the secondary from zinc when the primary β rays have passed through one sheet of zinc. It is seen at once from these curves that the radiations are not homogeneous, but travel at different velocities.

It is well known that a part of the secondary rays are deviable in a magnetic field, and in the same direction as the β rays would be. The magnetic deflections of the secondary rays from lead, and from paper, were tried by the method illustrated in fig. 10. The primary β rays from the radium enclosed in the lead box a striking the radiator b, produced secondary rays which passed up into the electroscope. Screens of lead c and d were



A
B
C
D
E
– Primary and Secondary Rays –
– Layers of Paper –
– % Absorption –
– Tertiary Rays –
– Layers of Paper –
– % Absorption –

Fig. IX.

so placed that the secondary rays from the radiator could just touch the upper edge E of the mercury screen. Experiments were performed with both lead and paper as radiators, and in both cases it was found, that the secondary rays produced were deflected towards the right, when a magnetic field was applied in such a direction, that the lines of force can be represented as going into the plane of the paper. The results obtained in this experiment are expressed in the following table (III).

TABLE III.

Field Strength	% Undeflected Rays	
	lead	paper
0	100	100
90	66	58
180	36	34
270	21	28
380	13	14
450	8	10

These results show that the secondary radiations from both metals and insulators consist for the most part of negatively charged particles. Those from insulators are more easily deflected than those from the more dense metals, but the difference is not very great. The proportion of non-deviable rays in the secondary rays from paper is greater than in that from zinc.

TERTIARY RAYS.

When the secondary radiation strikes upon objects there is produced a third type of radiation called the tertiary rays. This radiation has been studied in the

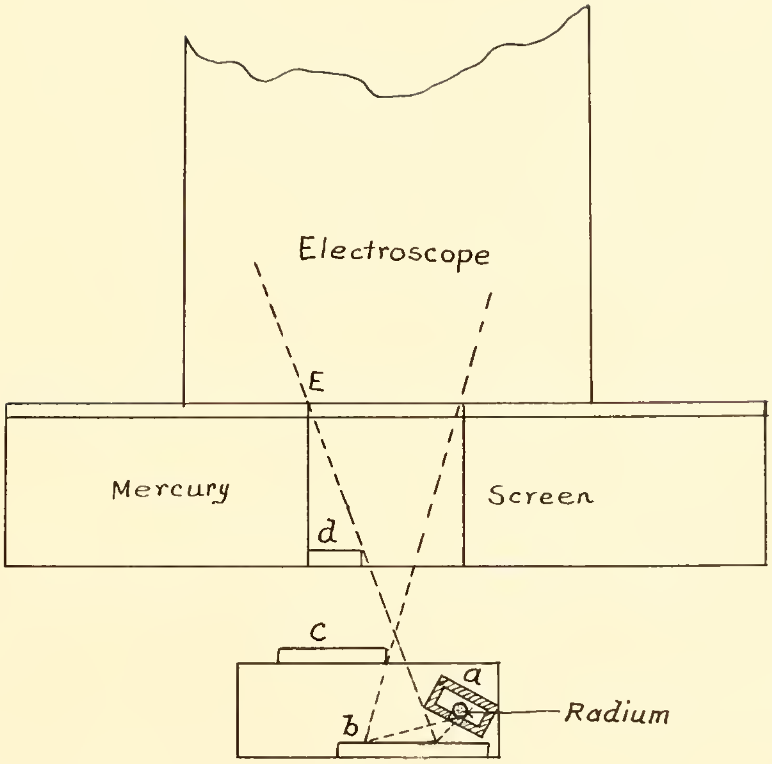


Fig. X.

present investigation for a few substances. The method employed was precisely the same as that used for the secondary rays, with the exception that the small glass tube containing the radium, instead of being placed in front of the opening in the lead box, was moved to one side so that no β rays could emerge from the opening. Under these conditions the β rays will strike the lead walls of the lead box and produce secondary rays which will travel out through the opening.

If we place a radiator in the same position as before, there will be produced in it tertiary rays, which can pass up to the electroscope, and cause an increase of ionization. The penetrating power of these rays was studied for lead, zinc, and copper radiators, and the results are expressed in the following table.

TABLE IV.

Layers of Paper	Tertiary Radiations		
	Lead	Zinc	Copper
0	100	100	100
4	59	46	47
8	35	25	24
16	17	10	11
24	6		2.4

As in the case of the secondary rays, lead proves to be the most efficient radiator, and also gives out the greatest penetrating rays. The penetrating power of the tertiary rays is considerably less than that of the secondary, that for lead in the former being only slightly greater than that for paper in the latter.

To find out whether the tertiary rays were deviable in a magnetic field, the arrangement shown diagramatically in fig. 11, was made use of. The mercury screen A was placed so that one end was directly over the ends of the ebonite blocks a and b. The electroscope B was placed near to the edge of the screen A, and had a window c covered with thin foil cut in one side, so that any rays might enter without absorption.

When the screen c was placed in position the tertiary rays produced could travel upward and enter the electroscope. Now by placing two screens, d and e, in the positions indicated in the figure, the rays could be prevented from entering the electroscope, but a portion would still be able to travel upward. When a magnetic field was applied in such a direction that the lines of force were perepndicular, and going into the plane of the paper, the ionization in the electroscope was not appreciably altered, but when applied in the reverse

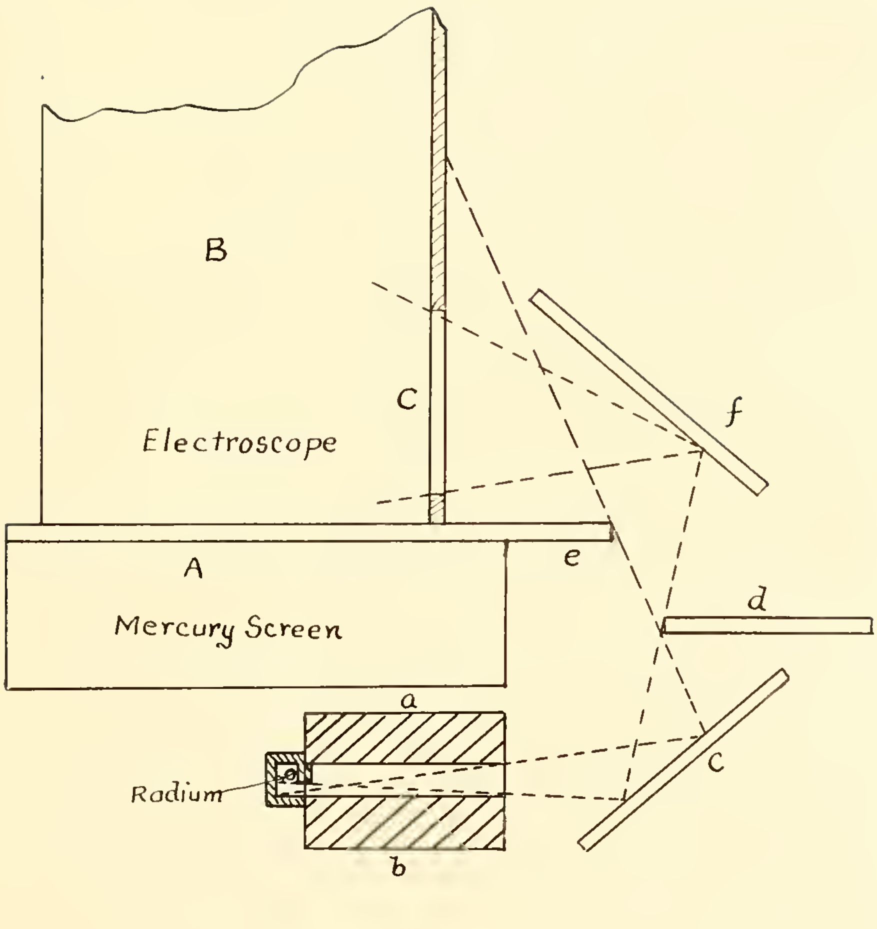


Fig. XI.

direction there was observed an increase in ionization. Moreover, when a screen was placed so as to cut off entirely the tertiary radiation from below, this effect was still observed but to a much less degree. These two results indicated that there was present, besides the tertiary radiation from below, a radiation which seemed to come from the mercury near the window of the electroscope. This latter radiation is undoubedly caused by the γ rays when they emerge from the surface of the mercury, and is the same as that observed by Eve[1] when the γ rays were partly absorbed by a thick block of lead. By placing sheets of paper in front of the window, it was found that the penetrating power of this radiation was much less than that of the tertiary; 4 sheets of paper cut it down to 30%, and 16 sheets completely absorbed it.

It was also obsevred that when the magnetic field was increased slowly from zero, a certain strength was reached at which the increase of ionization in the electroscope due to the tertiary rays from below just became noticeable. When this happened, the rays from below were bent so that the extreme edge of the beam just entered the window. Knowing three points on the circular path of the rays the radius of curvature could at once be

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1. loc. cit.

calculated, and was found to be about 17 cms. The strength of the magnetic field was about 90 C.G.S. lines, so that we get for the tertiary rays a value of $\underline{HR}$ = 1530 approximately. These results show that the tertiary rays are deviable in a magnetic field in the same direction as the β and secondary radiation. They must therefore be negatively charged particles travelling at speeds only a little less than the slowest β particles.

When the screen f is placed in the position indicated in the figure, it was found that the ionization in the electroscope was increased. This was found to be partly due to the secondary rays produced when the γ rays strike the screen, and also partly caused by the tertiary rays from below striking the screen, and producing a fourth type of rays.

That this latter radiation is present, can at once be shown by placing in front of the blocks a and b a screen, sufficient to cut off all the secondary rays, in which case the fourth rays are absent. This process would probably go on for a large number of radiators, but after the third the radiation is too feeble to be measured accurately. Each type of radiation is of less penetrating power than the one which produced it.

Velocity and ratio $\frac{e}{m}$ for the primary β rays.

It has just been shown that the secondary β rays have nearly the same penetrating power as the primary, and therefore, assuming for the present that they possess the same charge and mass, they must travel at velocities only slightly less. After passing through a certain thickness of absorbing material, the lower limit for both types of rays would be the same, and consequently the forward edge of a deflected beam would consist of both primary and secondary rays of the same velocity, which were just able to pass through the absorbing layer and cause ionization.

As the thickness of the absorbing layer is increased the less penetrating radiation would be more quickly absorbed, and at very thick layers, the edge of the deflected beam would consist almost entirely of the more penetrating radiation.

If then by any method we can find the forward edge of the deflected beam in both magnetic and electrostatic fields, we can at once calculate the velocity of those rays, both primary and secondary, which are just able to

causeionization after passing through the absorbing layer. The following method was then devised for this purpose and proved successful. It is shown illustrated in fig. 12.

Two zinc plates, a and b, were supported in a vertical direction, and insulated from one another by means of the ebonite blocks c and d. At the bottom of these blocks was fastened the lead box containing the glass tube of radium, and furnished with a slit 1 mm in width through which the rays emerged. At a short distance below the zinc plates there was placed a lead diaphragm with another slit also 1 mm in width, which formed with the opening below a narrow pencil of rays, which travelled upward between the zinc plates. The distance between the two slits was such that the rays from the radium just touched the top edges of the plates. This apparatus was placed inside a glass vessel A, which was closed at the top and bottom with brass plates B and C. Through the top plate B there was cut a rectangular opening 1.5 cms in width, and then covered with as thin a sheet of mica as would stand the pressure when the vessel was exhausted. The thickness of this mica window was about equivalent in absorbing power to 6 sheets of ordinary writing paper. The bottom plate C was pierced with three

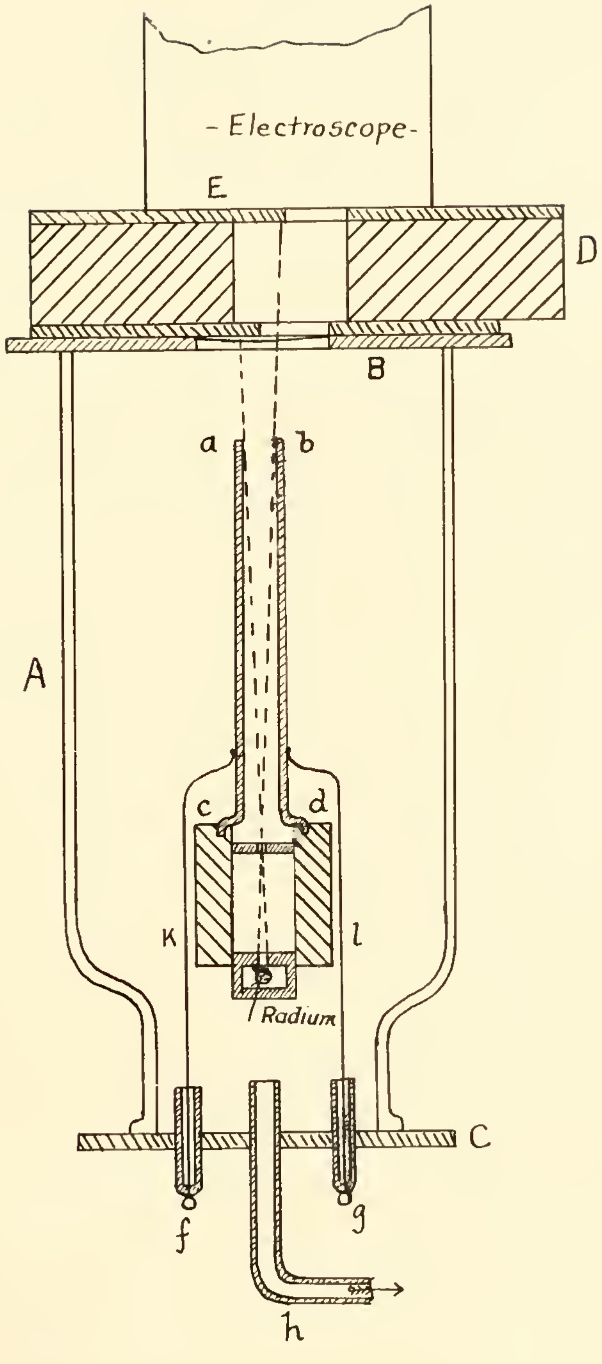

Fig. XII.

holes, into which glass tubes were fitted, two of them f and g containing the connecting wires K and l, and the third H serving to connect the vessel to the pump.

The whole apparatus was rendered air tight by the aid of sealing wax; and it was found, that with an occasional stroke of the pump the pressure could be maintained low enough to withstand a potential difference of 10000 volts without a discharge taking place.

By connecting the wires K and l to the poles of the battery of lead accumulators, the zinc plates could be charged up to any desired difference of potential. In the meantime the number of the cells had been increased so that a maximum potential of 3000 volts could be obtained.

On top of the brass plate B was placed the mercury screen D, described in the previous pages, which served to cut down in a large measure the γ rays. The opening in this screen was partly covered at the top by a brass plate E so placed that no β primary rays could enter the electroscope. The ionization in the electroscope would then be caused by γ, and secondary rays.

The vessel was placed between the poles of a large electromagnet, of such a size that the rays during their entire course lay in a uniform field.

When the primary rays strike the sides of the slits in the lead diaphragms, secondary rays are produced which travel upward with the primary to the electroscope. The pencil of rays at the electroscope is then made up of both primary and secondary radiation but will be prevented from entering by the brass screen F. This pencil of rays will, however, be confused by the presence of other secondary and tertiary rays coming from various points. This can be illustrated by some photographs taken at different points along the path of the rays. One taken 1 cm from the upper slit shows a narrow fuzzy image, whereas at 1 mm from the top of the zinc plates the image is sharp and the full width of the opening. At the top of the plate B the image had again become indistinct, while at the top of the mercury screen it was of the full width of the opening and of uniform density.

If the opening at the electroscope was arranged symmetrically with regard to the zinc plates, there was observed a decrease of ionization in the electroscope when the magnetic, or electrostatic fields were applied in either direction. The decrease in the case of the electrostatic field was about 25 per cent, with a strength of field of 14000 volts per centimeter. This shows clearly that the rays are deflectable in an electric field, though the effect observed was only about one

quarter as much as might be expected.

When, however, the arrangement was the same as that described in fig. 12, altogether different results were obtained. If the plate a were charged negatively, the ionization increased gradually to a maximum with increase of field, remained constant for a period, and then decreased. If, on the other hand, the plate a is positive the ionization decreased at once. The reason for this can be explained in the following manner.

If the plate a is charged negatively, the primary and secondary β rays will be deflected to the right, and enter the electroscope, thus causing an increase of ionization. This increase will continue until the rays have just reached the opposite side of the opening into the electroscope. When this is the case we can assume that those rays which after passing through the ~~absorbing layer~~ mica window can just affect ionization, are bent the most, since all rays of lower velocity, and hence penetrating power cannot get through. ~~the layer.~~ The same phenomena exactly were observed when a magnetic field was applied. Consequently when the maximum point is reached for both magnetic and electrostatic deflection, the value of the velocity of the slowest ray, which can just get through the absorbing layer, can at once be calculated from the values of the electrostatic and magnetic fields. When

different thicknesses of absorbing layers were placed over the opening, the strength of fields necessary to produce the maximum ionization was found to increase with increasing thickness of layer. This is what we would expect if the rays are of all different velocities, and shows, that when the maximum point is reached the least penetrating rays for each successive layer have all been bent through the same distance.

For the sake of illustration some of these results are expressed in the accompanying table (V).

TABLE V.

Through 6 sheets paper		14 sheets paper		1.5 mms. glass	
P.D.(volts)	Rate of Leak	P.D.(Volts)	Rate of Leak	P.D.(Volts)	Rate of Leak
0	144.0 sec.	0	151.0 sec.	0	154 sec.
2700	134.4 "	3300	144.2 "	4000	115 "
3000	132.4 "	3600	143.4"	5600	149.4 "
3300	131.6 "	3900	142.8 "	5800	148.6 "
3400	131.2 "	4100	141.5 "	6000	148.4 "
3500	131.0 "	4500	141.5 "	6800	148.6 "
3800	130.8 "	6000	141.4 "		
5000	130.6 "				
6000	130.6 "				
Max. 3500 volts -		4100 volts.		6000 volts.	

In this method we do not know how far each ray is bent, since we do not know its first position, and therefore cannot

obtain values of $\frac{mV}{e}$, and $\frac{mV^2}{e}$. But since the deflection is small compared to the length of the path, we can assume without any great error, that, for a maximum, this is the same for both magnetic and electric deflection. By comparing the electric and magnetic forces on the particle we can at once estimate its velocity. If d is the distance travelled by the ray in the uniform magnetic field H, l the length of the zinc plates, h the distance from top of plates to electroscope, X the strength of electric field, the velocity V is given by,

$$V = \frac{2X\,l\left(\frac{l}{2}+h\right)}{H d^2}$$

In this experiment, d = 17.0 cms. l = 8.4 cms, h = 5.5 cms, and the distance apart of the charged plates was 6.2 mms, therefore,

$$V = \frac{2X \times 8.4\left(\frac{8.4}{2}+5.5\right)}{17 \times 17 \times H} = \frac{0.563X}{H}$$

As an example take the results for an absorbing layer of 6 sheets of paper; here $X = \frac{3500}{0.62} = 5.7 \times 10^{11}$ C.G.S. and H = 13.5 C.G.S. lines, and therefore we obtain,

$$V = \frac{0.563 \times 5.7 \times 10^{11}}{13.5} = 2.37 \times 10^{10} \text{ cms / sec.}$$

In order to obtain values for $\frac{e}{m}$, it is necessary to know either $\frac{mV}{e}$, or $\frac{mV^2}{e}$ for the different rays. Values of $\frac{mV}{e}$ were obtained by the following method.

The lead box containing the radium tube was fastened to the ebonite blocks as before, but the distance between these narrowed to 2 mms, and the upper lead diaphragm removed. This arrangement allowed a broader pencil of rays than in the previous experiment to pass upward to the electroscope. Two zinc plates 3 cms in height were fastened to the ebonite blocks in a vertical direction and so arranged that one edge of the pencil of rays could just touch the top of the one of the plates. The effect of this upper plate was then to define sharply a pencil of both primary and secondary rays. This arrangement was then surrounded by a magnetic screen of soft, sheet iron which extended up to the top of the zinc plates, and kept the rays during their passage between the plates from the action of the magnetic field. The glass vessel was dispensed with and the experiment performed at atmospheric pressure, sheets of paper equivalent in absorptive power to the mica window of the previous experiment being interposed in the path of the rays. The opening at the electroscope, 1 cm in width was arranged as in the other experiment so that no rays of this pencil could enter the electroscope.

When a magnetic field was applied in the proper direction the ionization in the electroscope gradually in-

creased to a maximum as the strength of the field was increased. Since the rays are only under the action of the magnetic field during their passage from the top of the zinc plates to the electroscope we can assume, that, when the maximum point is reached, the least penetrating rays have been deflected over the distance represented by the width of the opening. By placing in the path of the rays suitable thicknesses of absorbing material the value of $\frac{mV}{e}$ for the same rays as were observed in the previous experiment could be ascertained.

These values were calculated from the following formula, - (See J. J. Thomson'S, Discharge of Electricity through Gases, page 92.

$$\frac{mV}{e} = \frac{1}{2\delta}\int dx \int H\,dx$$

where δ = the distance through which the rays are bent, and H the value of the magnetic field at different points along the path x of the rays. The value of $\frac{mV}{e}$ obtained by this method was 1.57×10^3 for no absorber, whereas, for 1.2 mm of zinc it was 5×10^3; for 6 sheets of paper corresponding to the mica window the value was 1.87×10^3.

In the former experiment in the uniform field the value of $\frac{mV}{e} = \frac{Hd^2}{2\delta}$, and substituting the ~~above~~ value of $\frac{mV}{e}$ obtained above we get for the distance through which the rays were bent 1.0± cms. Knowing this value of δ, all the remaining values can at once be calculated, and the complete results are shown in the

following table (VI).

TABLE VI.

absorbing Layer	I(max)	H(max)	$\frac{mV^2}{\varepsilon}$	$\frac{mV}{e}$	V cms/sec	$\frac{e}{m}$
0				1.57×10^{3}	2.20(est.)	1.40
6 of paper	5.7×10^{11}	13.5	4.4×10^{13}	1.87	2.37×10^{10}	1.27 x10
10 "	6.1 "	14.3	4.76	1.98	2.40	1.21
14 "	6.6 "	15.1	5.15	2.10	2.45	1.17
18 "	7.2	16.2	5.62	2.25	2.49	1.10
22 "	7.7	17.0	6.01	2.36	2.54	1.07
30 "	8.3	17.9	6.47	2.49	2.60	1.04
1.5mm glass	9.6	20.0	7.49	2.78	2.69	.96
.3 copper	11.0	22.2	8.58	3.09	2.77	.90
0.4 zinc	14.0	27.2	10.92	3.79	2.88	.76
.8 "				4.60	2.95(estimated)	.64 *
1.2 "				5.00	2.97	.59 *

As has already been explained, the values given in the above table will represent those for both the primary and secondary particles which are just able to penetrate through a certain absorbing layer and still cause ionization; the highest values of the velocity are those for the β particles alone, since nearly all the secondary particles are absorbed in about

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* These estimated values were extrapolated from the curve showing the relation between the velocity and $\frac{mV}{e}$.

35 sheets of paper. The values of the velocity for the particles through 0.8 and 1.2 mm of zinc could not be obtained for the reason that the limit of the available difference of potential had been reached. The values of $\frac{mv}{e}$ for these, however, show that the apparent mass of the particles is increasing rapidly as the velocity of light is approached. The lower limit of the β rays cannot be stated with any certainty but it is probably greater than 2.3 x 10^{10} cms per sec. The β rays in all the experiments had first of all to pass through the thin glass walls of the tube, which would probably absorb about as much as the mica window.

The results given in the above table agree very well with those obtained by Kaufmann[1] in his later experiments, using an entirely different method, and show beyond doubt that the β particles from radium travel with speeds approaching that of light, and further that their apparent mass does increase with the speed.

In Kaufmann's experiment secondary radiations must have been present in quantities quite comparable with the primary, and consequently any point chosen on his curved photographic traces would represent not alone the primary particle, but also some secondary particles which happened to arrive at the same point. If the primary and secondary

1. loc. cit.

particles differed in velocity there might possibly be some difficulty in estimating the radii of curvature for the different rays. He has compared his results with those calculated from the theoretical formulae of Abraham, and finds a very close agreement, thus giving considerable evidence to the view that the mass of the electron is entirely electrical in origin, and increases as the speed approaches that of light. The result of the present investigation also seems to lead to the same conclusion. We must, however, remember that the confirmation of this theory is only over a short range where the increase of the apparent mass is not very great, and where any set of values might accidently agree very closely with the theoretical. It is not until the speed has, for all experimental purposes, practically reached that of light that there is any great increase of the apparent mass, and consequently any confirmation of the theory over a long range is entirely beyond experimental means. Moreover the assumptions made in the deviation of the theoretical formulae, and also in the formulae used to calculate the velocities and ratio $\frac{e}{m}$ from the experimental data, are many and somewhat great. It is assumed that the same laws of electric and magnetic

force apply equally well as very high speeds as at comparatively low, something of which we have no a priori knowledge. A divergence of either, or both, of these laws at high speeds could account for the experimental facts observed.

However considering all sources of error the results of Kaufmann, together with those of the author lend great weight to the view that the mass of the electron is electrical in origin, and increases with the speed.

Velocity and ratio $\frac{e}{m}$ for the secondary β rays.

It has been assumed in the previous sections that the velocity of the secondary rays was only slightly less than the primary, and also that they carried the same charge and had approximately equal masses. That these facts are true was proved by the following set of experiments.

The general arrangement of the experiments was the same as that used in the case of the primary rays, and the same drawings and general description will suffice here. The tube of radium, instead of being placed underneath the slit in the lead box, was shifted to one side

so that no primary rays could emerge from the box. The lead box was fastened to the ebonite blocks so that the slit was near the right hand block, and not in the middle as was the case with the primary rays. The upper lead diaphragm was removed and in its stead was fixed a strip of lead, which covered one third of the opening between the blocks. The secondary rays on emerging from the slit in the lead box could strike full upon the left hand zinc plate, but were prevented by this strip of lead from falling upon the right hand plate. The rest of the arrangement was precisely the same as for the primary rays, the opening at the electroscope being arranged so that no secondary rays from the lead box could enter.

The secondary rays when they strike the left-hand plate, and also the edge of the lead strip produce tertiary rays which travel up with the secondary rays. A great part of these will be absorbed by the mica window but some will get through and cause ionization in the electroscope. There is also a small amount of secondary rays produced by the rays striking the various parts of the apparatus; these, however, do not affect the results since they come from all different parts of the vessel, and are therefore deflected very unequally.

When the electric or magnetic fields were applied in the same directions as in the case of the primary rays the same phenomena were observed; a gradual increase of ionization to a maximum with increasing fields, in one direction, and a decrease at once with the field in the other. The same absorbing layers were used in this case as in that of the primary rays. It was found that no increase of ionization above 30 layers of paper could be observed, that thickness being sufficient to almost completely absorb the secondary rays. These results confirm the idea that the secondary rays have a less penetrating character than the primary, and travel at lower speeds.

In order to estimate how far the rays were bent in the electric and magnetic fields the same method was used as for the primary rays. All that was necessary to do was to shift the tube of radium from beneath the slit in the lead box to one side so that no primary rays could get out. The soft iron screen was placed so that the rays were shielded from the influence of the field until they had passed the top of the zinc plate. The distance from the top of the zinc plate to the electroscope was less than in the case of the primary rays, but the width of the opening in the electroscope the same. The value of $\frac{mv}{e}$

for no absorbing layer was found to be 1.56×10^{3}, and for an absorbing layer of 6 sheets of paper was 1.85×10^{3}. These values are about the same as the corresponding ones found for the primary radiation, and show that the lower limits in the latter case were those of the secondary rays. The upper limit for the secondary rays by this method was also the same as by the other method, viz., 30 layers of paper.

Substituting these values of $\frac{mV}{e}$ in the results obtained by the first method we obtain 1.29 cms as the distance through which the rays were deflected.

In this experiment, l = 8.4 cms, h = 5.5 cms, and d = 17.3 cms, and therefore,

$$V = \frac{2 \times 8.4\left(\frac{8.4}{2} + 5.5\right)}{17.3 \times 17.3} \frac{X}{H} = 0.544 \frac{X}{H}$$

In the accompanying table(VII) are expressed the final results obtained for the secondary rays.

TABLE VII.

Absorbing Layer.	X(max)	H (max)	$\frac{mV}{e}$	V cms/sec	$\frac{e}{m}$
0	+	-	1.56×10^{3}	-	-
6 paper	6.9×10^{11}	16	1.85	2.35×10^{10}	1.27×10^{7}
14 "	7.5 "	17	1.97	2.40 "	1.21 "
22 "	8.5	18.5	2.16	2.50 "	1.16 "
30 "	9.6 "	20.3	2.30	2.58 "	1.09 "

It will be seen at once from this table that the values of the velocity and ratio $\frac{e}{m}$ for the secondary rays are in good agreement with those obtained for the primary. Since the experiments on the secondary radiations from different substances, described earlier in this paper, showed that they were all deflected in a magnetic field, and since further that the penetrating power of the rays were not greatly different, we can conclude that both metals and dielectrics give off when struck by β rays, negatively charged particles with velocities, and ratio $\frac{e}{m}$, the same as those for the less penetrating β rays.

As to the origin of these secondary and tertiary radiations, two possible explanations can be given. They might be the primary β particles reflected back from the molecules of the bombarded substance. The other and much more probable view is, that, the secondary radiations are produced when the primary β rays, striking the atoms of the substance, cause them to give off one or more of the electrons of which they are composed, with sufficient velocity to escape from the substance. The longer the path, and the greater the number of atoms which a β particle encounters before it is absorbed, the greater will be the amount of the secondary radiation produced. The nature and amount of the secondary radia-

tions produced will depend on the nature of the atoms of the substance and on the density. The production of secondary and tertiary radiations is not similar in this respect to the production of β rays by the radioactive substances; in the latter case the effect is as far as we know spontaneous, in the former it is due to external agents.

Conclusion.

It will perhaps be instructive to briefly summarize here the main facts brought out in the present investigation.

The difficulty experienced at first in obtaining an electrostatic deflection of the β rays was due entirely, or mainly, to the disturbing action of the secondary and tertiary radiations.

When this disturbing action had been eliminated by the later methods adopted, values of the velocity, and ratio $\frac{e}{m}$, were obtained which agreed closely with those found by Kaufmann using an entirely different method.

A great part of the secondary radiations, which are produced when the primary β rays strike upon an absorbing material, are composed of negatively charged particles travelling at speeds nearly equal to that of the β

rays themselves, and having the same ratio $\frac{e}{m}$ for corresponding velocities. The secondary rays themselves, when incident upon a substance, produce tertiary rays, which are of slightly less penetrating character, are deflectable in a magnetic field in the same direction as the secondary and primary β rays, and are probably of the same nature as these.

The values of $\frac{e}{m}$ obtained for both the primary and secondary β rays showed, that the apparent mass of the particles increased as that speed approached the velocity of light.

Taking for granted that the assumptions involved in the calculations of the velocity, and $\frac{e}{m}$, are correct, my results together with those of Kaufmann furnish evidence in favour of the view that the mass of the electron is entirely electrical in nature.

In conclusion I wish to express my sincere thanks to Professor Ames for his kindly interest, valuable suggestions, and for the facilities which he placed at my command during the progress of this investigation.

Johns Hopkins University,

Baltimore, Md.

March, 1906.